

Plasma Formation Studies and Plans for the Pegasus Toroidal Experiment*

by T. A. Thorson for the Pegasus Group University of Wisconsin–Madison U.S.A.

An extremely low-aspect ratio facility exploring quasi-spherical highpressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

• Explore the extreme limit of low-aspect ratio physics



^{*}Supported by U.S. DoE grant No. DE-FG02-96ER54375





Role of the PEGASUS Experiment

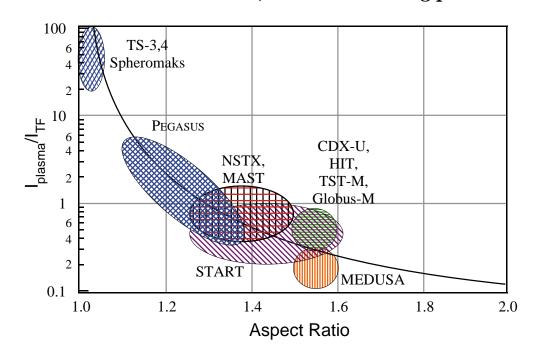
• Contribute to development of the Spherical Torus (High q_{ψ})

- Extreme toroidicity $(A \rightarrow 1)$
- Current limits and disruptivity
- β limit dependence on A, κ , etc.
- Confinement with aux. heating at A < 1.3
- New startup schemes (e.g., plasma gun current injection)

• Address physics of A ightarrow 1 as an <u>Alternate Concept</u> (Low q_{ψ})

- Very high TF utilization $(I_P/I_{TF}) > 3$;
- Trade-offs: CD, recirculating power, and $A \approx 1$, low-TF operation
- MHD equilibrium and stability at very low TF ($\beta \approx 1$)
- Explore RF heating and CD schemes (HHFW, EBW)

$A \rightarrow 1 \Rightarrow$ smaller centerstack, less recirculating power and waste







Pegasus Operates at Ultra-Low A via Reinforced, High-Stress Solenoid





PEGASUS Operational Parameters

<u>Parameter</u>	Present	Full
Α	1.16 - 1.3	1.1 - 2.0
R	0.2 - 0.3 m	0.2 - 0.45 m
Ip	0.1 MA	0.1 - 0.3 MA
B _t	≤ 0.1 T	≤ 0.15 T
ĸ	~ 1.5 - 3.0	~ 1.5 - 3.7
$\Delta t_{\sf pulse}$	3 - 8 msec	30 - 60 msec
β_{t}	0.03 - 0.2	O(1)
β_{N}	1 - 5	> 5
I _N	~ 2-6	> 10
Heating and Sustainment	Inductive*	Inductive*+ RFCD (HHFW, EBW), Plasma Guns

^{*} NHMFL: B_{solenoid} = 10 - 14 T





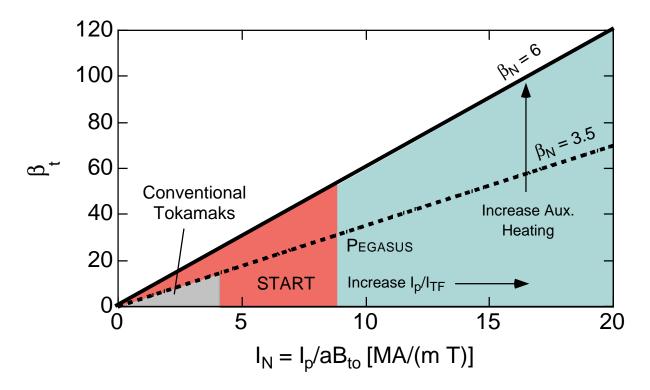
Goals of the Pegasus Toroidal Experiment:

Primary Goals:

- Plasma stability limits at high I_p/I_{TF} , low A, high κ
- Operational limits (in terms of q_{ψ} , density, β , κ , A, etc.) for $A \rightarrow I$
- Demonstrate access to high β_t at extreme I_N without a close-fitting conducting shell.

Secondary Goals:

- Test relaxation stability at tokamak/spheromak boundary
- Measure global confinement characteristics for varied A, κ, etc.
- Evaluate the need for external CD as $A \rightarrow 1$
- Evaluate plasma guns for startup and j(R) modification
- Initial studies of startup, heating, and CD via EBW launch

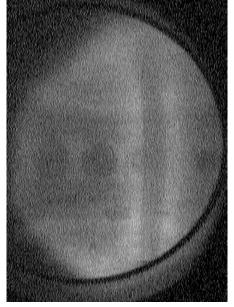






First Campaign: Plasma Formation Studies

- Demonstrated efficient startup and startup at low B_t in presence of conducting walls
 - Critical for low TF, high β mission for Pegasus
 - Induced wall currents are reasonably understood and accounted for
 - Startup achieved at $B_{to} \sim 0.05$ T, startup at 2 V possible at full field
- Accessed a variety of plasma geometries

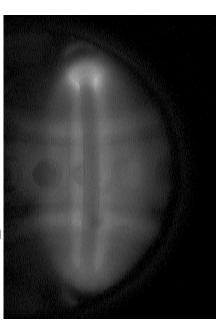


$$R = 0.34 \text{ m}$$

 $a = 0.29 \text{ m}$
 $A = 1.17$
 $\kappa \approx 1.8$

$$R = 0.2 \text{ m}$$

 $a = 0.15 \text{ m}$
 $A = 1.3$
 $\kappa > 3$



Geometric Plasma Properties Estimated from Visible Images





Startup Plasmas Show ST Characteristics

• ST-like behavior observed:

- Fast plasma current ramps (20 100 MA/sec)
- High natural elongation
- MHD: IRE's and tearing modes observed

• Initial plasmas beginning to access low TF, high β_t regime

- High β_t , normalized β $\beta_t \sim 20\%$, $\beta_N \sim 5$

- High density $n_e \sim n_G$

- High TF utilization factor $I_p/I_{TF} \sim 1$

- High normalized current $I_N \sim 6$

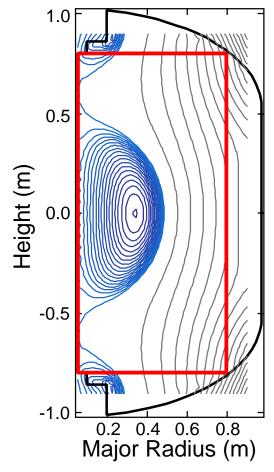
Full power, long pulse operation anticipated by OH completion

- Pulse extended from ~ 5 to 30 ms
- I_p raised from 0.1 to 0.3 MA



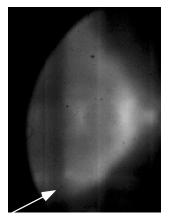


Moderately High β_t Accesible in OH Plasmas



Shot 4699

$$\begin{array}{lll} R &= 0.27 \text{ m} & I_P &= 0.065 \text{ MA} \\ a &= 0.22 \text{ m} & \beta_{pol} = 0.6 \\ A &= 1.22 & l_i &= 0.35 \\ \kappa &= 2.1 & \beta_t &\approx 0.22 \\ I_{TF} &= 0.09 \text{ MA} & \beta_N &= 4.9 \\ q_a &\approx 7 & q_0 &\approx 1.5 \end{array}$$



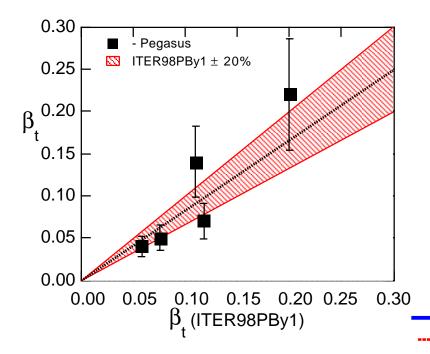
Ohmic Solenoid

- Equilibrium reconstruction using 6-8 B_p coils & 4-6 fluxloops
- Visible image used to constrain position and size
- Density, spectroscopy and confinement consistent with fit pressure



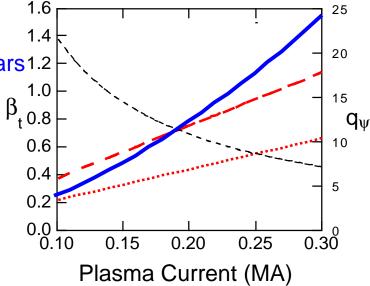
First Results: Promising for Full-Power Operation

- Estimates of β_t consistent with START scaling
 - Experiment β_t estimated from magnetic equilibrium
 - Min. diagnostics, P_{Rad} , Z_{eff} , τ_{pulse} , etc. \rightarrow large uncertainties
 - 0-D confinement model with ITER98PBy1 τ_E scaling for expected β_t



Intereseting plasma regime appears 1.2 accessible with OH only

- Lower collisionality and challenge stability limits with more flexible shapes via auxiliary heating



Full-Size Pegasus (w/ITER98pby1; OH)

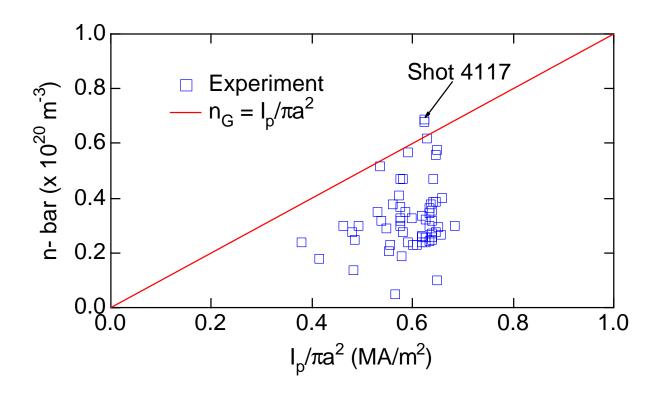
 $\beta_{N} = 6.0$

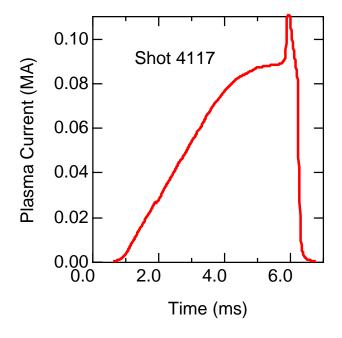
 $\beta_{\rm N}=3.5$

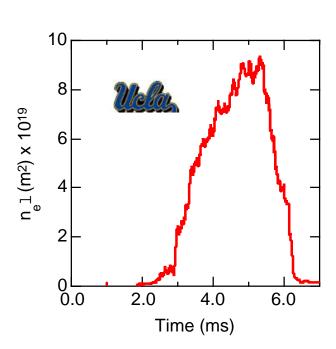




Plasma Density Approaches Greenwald Limit



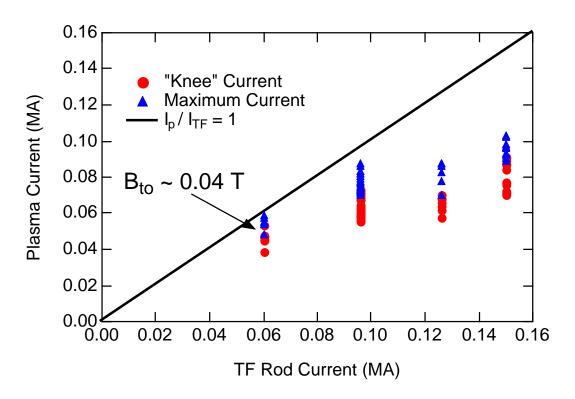




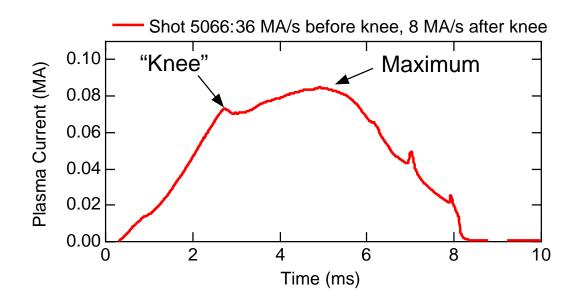




$I_p/I_{TF} \rightarrow 1$ at Lowest TF Settings



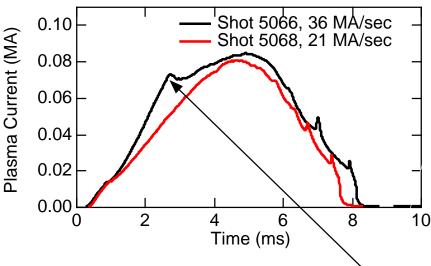
- Present limits on I_p/I_{TF}: ramp rate and pulse length
- Tearing modes limit I_p ramp rate → High I_p/I_{TF} only at low TF



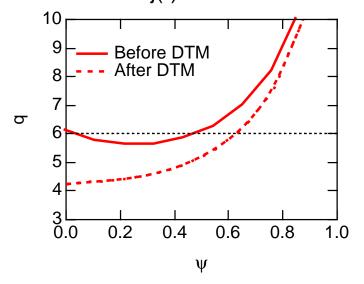




Double Tearing Modes Limit Plasma Current Ramp Rate

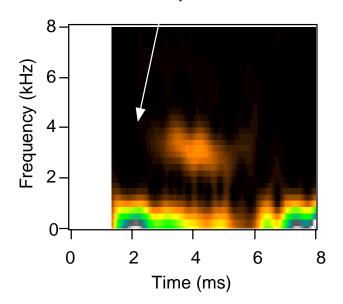


Similar events on MEDUSA identified as DTM's with internal j(r) measurements



q profile flattens and current penetrates into the core after the DTM

Shot 5066: m=2 mode after "knee" in plasma current



m = 2 activity observed on Mirnovs and interferometer

I_p ramps up to 30 MA/sec are stable





Pegasus Research Program Overview

Low-q/low-TF stability studies in full power OH plasmas

- Full power, large OH plasma development
- *Low-q limits* @ *A* < 1.3
- Limits of I_p/I_{TF} operation
- Loading and coupling tests for HHFW antenna
- j(R) via SXR imaging tests
- Test separatrix/divertor operation
- Tests of plasma gun injection

• High β stability and high power RF auxiliary heating

- MHD stability limits: shaping, profiles, configuration effects
- β_t limits with auxiliary heating and DC TF
- Confinement evaluation

Exploration of high β stability at high and low edge q

- Kink and ballooning stability limits
- Tokamak/spheromak stability boundary with TF rampdown
- Tests of EBW heating

• Status: Feb 2000

- Ending maintenance period: OH power supply completion
- Operations expected early March



Investigate Tokamak-Spheromak Transition

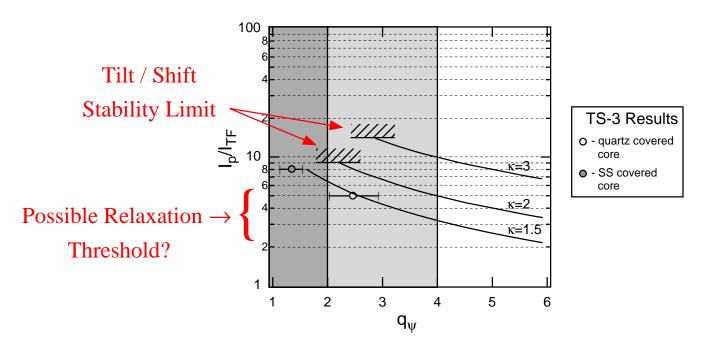
Determine limit of low TF operation

- As $TF \rightarrow 0$, a transition from a stable tokamak configuration to a unstable spheromak-like plasma is expected
- This transition defines the lower limit of B_t
- Explore transition behavior with geometry, j(R), β , etc.

Taylor relaxation may occur at lower Ip/ITF

- $\lambda a > 2.4$ ($\lambda = j_{//}/B_{tot}$) suggests the onset of relaxation and/or increased MHD in Pegasus for $I_p/I_{TF} \ge 2$
- The above relation assumes a cylindrical geometry torodicity may increase the I_p/I_{TF} limit for Pegasus

Pegasus expected to be tilt/shift stable at relaxation threshold



Takes advantage of new, low-inductance TF centerstack



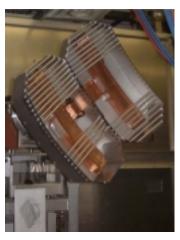


Development Activities Continuing

OH power supply development near completion

- Step-down transformer for impedance matching and double-swing
- Longer pulse, more flexible waveform control

RF heating system development continuing



- 1-2 MW HHFW heating system
- First-generation antenna fabricated; install Spring 2000
- 0.5 MW tested into dummy load

Internal hardware upgrades due during RF install

- More complete centerstack protection and upper/lower limiters
- Increased coverage with magnetics diagnostics

Next-generation centerstack in fabrication

- Low inductance TF circuit
- Ramp down power supply in development

Advanced diagnostics in design

- j(R,t) from SXR 2-D imaging and Li pellet injection (PPPL help)
- $T_e(t)$ from EBW radiometer
- N_e profiles from beam fluorescence
- Tilt angle from Reflectometry (UCLA)





Summary

- Primary goal is to explore the A → 1 regime
 - Geometry (A, κ , separatrix) and current profile (\mathcal{L}_i , q_o , q_{ψ}) influence on the stability limits?
 - Tokamak/Spheromak Overlap: How close can $A \rightarrow 1$ and maintain good stability and confinement?
 - Tradeoffs between $A \approx 1$ and current drive requirements?
- Starting to access interesting low TF, ST regime
 - $I_p = 0.1 \, MA$
 - $n_e \sim n_G$
 - $\beta_t \sim 20\%$, $\beta_N \sim 5$
 - Startup up at 60 kA of TF rod current ($B_{to} \sim 0.05 T$)
 - $I_p/I_{TF} \approx 1$, $I_N \sim 6$
 - Completion of OH will allow for longer pulses, higher I_p
- Near-term goals concentrate on exploration of low-TF ohmic operation
 - High field utilization
 - Equilibrium and stability as $A \rightarrow 1$
 - Initial RF operation





Pegasus has Benefited Greatly from Contributions from Members of the Fusion Science Community:

Collaborations

NHMFL: Solenoid design, fab., tests

Stress Analyses; VV construction;

Theory (MHD, RF...); Future expts.

PPPL: RF; Power Engr.; DNB assistance

UCLA: µwave interferometer

MST: Engineering; diagnostics; e-gun j sources

Contributions

NHMFL Magnets

General Atomics Vacuum Vessel, Iron core

PPPL Capacitors; diagnostics; CAMAC

LANL Caps; Ignitrons, RF systems

MST Ross diodes; iron core; caps, etc.

HSX EF cap bank

LLNL Caps; DNB power system

ORNL Thomson scattering

Westinghouse High-E cap bank

UW SC Lab: TF hex conductor